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(71) Applicant *(for all designated States except US)*: CALIFORNIA INSTITUTE OF TECHNOLOGY [US/US]; 1201 East California Boulevard, Pasadena, CA 91011 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: SMEDLEY, Gregory, T. [US/US]; 81 Whitman Court, Irvine, CA 92715 (US). FLAGAN, Richard, C. [US/US]; 1032 Lavender Lane, La Canada, CA 91011 (US).

(74) Agent: HARRIS, Scott, C.; Fish & Richardson P.C., Suite 1400, 4225 Executive Square, La Jolla, CA 92037 (US).

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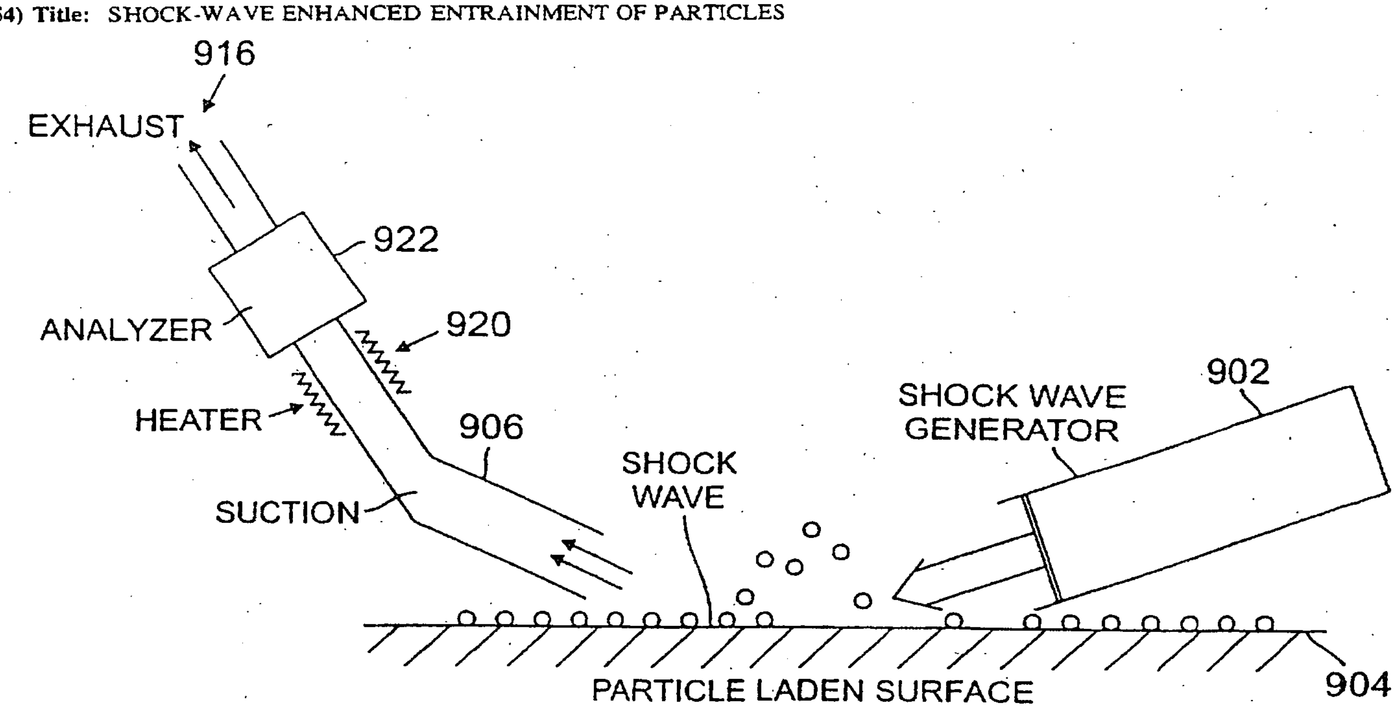

(57) Abstract

A method and system using shock waves from a shock wave generator (902) to remove small particles from a surface (904). A shock wave produces an abrupt increase in the velocity, the pressure, and the density of the fluid behind the shock wave as it travels. The combination of the high density and the high shear caused by the shock wave on a surface (904) creates a strong drag on particles adhered to the surface (904), thus promoting removal of the particles. This allows non-invasive and efficient cleaning of sufaces (904) and detection/identification of explosives and drugs on surfaces (904) with an associated analyzer system (906, 916, 920, 922).

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SHOCK-WAVE ENHANCED ENTRAINMENT OF PARTICLES

Origin of the Invention

The United States Government may have certain rights in this invention pursuant to grant number 93-G-060 awarded by the Federal Aviation Administration (FAA).

Field of the Invention

The present invention relates to removal of small particles bound to surfaces. More particularly, the present disclosure describes a technique and a system for efficiently entraining small particles from surfaces using shock waves in surface cleaning systems and on-line chemical analyzing instruments.

Background and Summary of the Invention

Small particles often tenaciously adhere to a surface upon which they are deposited. These particles can be considered as unwanted contamination or as desirable evidence depending on the particular application. Foreign particles deposited on substrates are a concern in the semiconductor industry since they can be responsible for creating defects in the etched features and lead to reduction in the product yield.

In the science of detection of low volatility substances such as explosives and drugs, identification of the tenacious particles of these substances may provide evidence of the presence of the substances thereof. Subsequent removal and analysis of the content of these particles can enhance the possibility of

identifying the presence of such low volatility substances by relying on a very small amount of residue. Detection of explosives or illegal substances that are contained in luggage at airports is one example of many applications of such a sampling technique.

Therefore, techniques to effectively remove small particles from surfaces constitute an important element in both surface cleaning and substance detection. In particular, it is desirable that such particle-removing techniques preserve the quality of a surface from which the tenacious particles are removed. For applications such as cleaning semiconductor substrates, it is often desirable to maintain the quality of the surface of the substrate at a submicron scale. For detecting explosives in luggage, the sampling technique should not cause any marks on the luggage surface, which is a much less constraining requirement than that in cleaning semiconductor wafers.

Several methods for the removal of minute particles from surfaces have appeared in the art. These include particle removal using gas jets and gas jets with particles, Laser Assisted Particle Removal ("LAPR"), and particle removal using a high-decibel acoustic field. The goal of each of these methods is mainly to remove particles without damaging the surface to which they adhere.

In many cases, other than LAPR, efforts are made

to penetrate the boundary layer that forms on a surface and shelters the small particles from the higher velocity of the bulk fluid flow past the surface. LAPR utilizes an energy transfer medium to absorb the laser energy and thus explosively release the particles from the surface.

The utilization of gas jets to remove particles from surfaces is a common approach that each of us has used in everyday life when trying to blow dust off a piece of paper, a piece of furniture, or an old instrument. The common observation is that it is better to blast air quickly from tightly pursed lips so as to produce a short burst of air at a high speed than to blow air steadily to the surface.

A steady-state air jet establishes a stabilized boundary layer on the surface. This boundary layer prevents penetration of high speed fluid to the level of bound particles on the surface, that is, particles are buried in the boundary layer so that high speed fluid does not reach them. Puffing produces a thinner boundary layer yielding higher shear and high speed fluid near the surface so that particles can be removed more effectively. Continuing to blow at constant speed after the initial burst rarely produces additional particle removal unless the particles are quite large. However, following the first puff with a series of puffs usually leads to additional particle removal. This technique was investigated by Otani, et. al. They found that particle

removal in excess of 85% could be achieved after several blasts of air with each blast lasting about one second. Otani et al. also showed that using a steady-state jet failed to remove additional particles after the first second, even when it was left on for two minutes. Presumably, once the boundary layer is set up on the surface, the shear imposed on the particles is insufficient to remove them.

One way to penetrate the boundary layer of the steady-state impinging jet or a puffing jet is to seed the jet with small particles. It is desirable that the inertia or momentum of these particles is high enough so that they do not follow the streamlines of the gas jet as it is deflected by the surface. These high-speed particles of a seeded jet physically collide with the particles that adhere to the surface. A transfer of momentum from the seeded jet particles to the surface particles can be sufficient to cause the surface particles to be removed from the surface if the momentum of the seeded jet particles is large enough. The removed surface particles are further entrained into the jet flow. Aspects of this technique were investigated by Walter John using a gas jet at normal impingement. Particles were removed from the surface and measured with a particle counter downstream of the impact area.

Another method of penetrating the boundary layer on a surface was proposed by Montz, et. al. This method

used a high-decibel acoustic field in combination with a low-speed cleansing flow that prevents redeposition of the removed surface particles. Montz believed that periodic high-decibel acoustic waves promoted the removal of small particles by the generation of acoustic turbulence, vorticity, and acoustic winds. Montz also stated that the periodic high-intensity acoustic signal should disrupt the boundary layer containing the contaminant particles. The intensity of the acoustic waves that were necessary to remove small particles were in the range of 1 to 10 W/cm^{-2} (i.e., 160 to 170dB). The actual pressure P and the maximum fluid velocity u_{max} produced by sound waves are given by:

$$P = \sqrt{2\rho_o c I}, \quad (1)$$

$$u_{max} = \frac{P}{\rho_o c}, \quad (2)$$

where ρ_o and c represent the undisturbed air density (1.21 kg/m^3) and sound speed (343 m/s) in air at 20°C and I represents the intensity of the sound in W/m^2, respectively. Accordingly, the pressures imposed by these sound waves were in the range of 2.9 to 9.1 kPa.

The maximum gas velocity u_{max} that resulted from the passage of these sound waves was in the range of 6.9 to 22 m/sec. Montz concluded that this cleansing technique could be effectively used on particles greater than 30 mm in diameter.

The Laser Assisted Particle Removal (LAPR) method relies upon the introduction of an energy transfer medium that absorbs sufficient energy from the laser light to explosively evaporate and thus dislodge bound particles from a surface. The laser wavelength and energy transfer medium are selected such that light absorption by the surface being cleaned is small while light absorption by the energy transfer medium is large. This selection process is essential to prevent damage to the surface by the intense laser radiation. In the event that the particles are considered undesirable contamination, damage to the particles themselves is of little concern. However, if the particles are considered to be desirable evidence, then a high powered laser cleaning method may not be the method of choice. Initial LAPR experiments reported by Imen et al. were directed at cleaning alumina powder from silicon substrates using water vapor as the energy transfer medium and a pulsed CO_2 TEA laser operating at a wavelength of 10.6 mm as the energy source. They found that 1 mm diameter particles could be easily removed from the substrate with a few 55mJ pulses

from the pulsed CO_2 laser.

In LAPR, the explosive evaporation of the energy transfer medium by the energetic laser pulses could produce shock waves that might damage the surface. Lee, et al. reported on experiments in which the propagation of a spherical shock was measured. The presence of the shock verified that shock waves could be generated by explosive evaporation but the threshold for significant shock wave generation was almost twice the threshold necessary for particle removal; therefore particles could be removed from the surface without significant shock generation and thus the possible damage thereby. It was desirable in LAPR to avoid the production of shock waves that might damage the substrate through spallation or scratch. In their experiments they produced and measured shock waves up to Mach 1.8, i.e. with a propagation velocity of 630 m/sec.

The inventors recognized various limitations of the prior-art methods for particle removal. For example, the gas jet method tends to build up a boundary layer that may prevent quick and efficient removal of particles from a surface even with a puffing jet. Also, continuous gas jets of modest size, operating at a pressure necessary to remove small particles, consume the compressed gas at a high rate.

Particles can be removed from a surface by impacts of particles entrained in the gas flow, but the particles

must be tailored for the particular particles that are to be removed and may damage the underlying surface. Semiconductor wafers have been cleaned by impact of solid particles produced by condensation of a vapor in a rapidly expanded gas. The development of a boundary layer in the impinging jet flow, and the need to probe complex surfaces introduce added complications into the design of such particle removal systems. In addition, this method has the added complication of tailoring the particle size that is created by an expanding/cooling gas jet (e.g., argon or CO_2). If the particles are not created as a result of gas expansion/cooling, it is then necessary to introduce particles into the high-pressure impinging gas stream.

Laser Assisted Particle Removal (LAPR) relies on the introduction of an energy transfer medium such as water vapor around and below the adhered particles on a surface. It may not be possible or practical to employ this method for cleaning or sampling some materials that are adversely affected by the energy transfer medium. In addition, the use of a high powered laser may limit its usefulness in many applications. It is also possible that in the event that the particles are considered valuable evidence, this method may damage the evidence. The fact that the energy transfer medium must strongly absorb laser light at a wavelength that a target surface does not absorb or has a minimum absorption limits the

use of the LAPR method. Furthermore, the LAPR technique introduces a number of other problems in luggage sampling including eye safety among security personnel and passengers, and laser damage to the luggage.

Using high-decibel acoustic waves is not practical in many cleaning and sampling applications because very high-powered amplification systems are needed to create the strong acoustic waves. This is due to the low efficiency inherent in the technique and a lot of power is required to produce only modest fluid velocities near the surface. In addition, high amplitude continuous sound near 160 dB is not desirable in many environments, especially in airport security operations. The requirement of establishing standing waves is also a limiting factor to this method.

The particle removal methods discussed above are primarily used for cleaning surfaces. There are other applications that require the removal of particles from surfaces. One example is sampling procedures in chemical detection including vapor detection systems. The current sampling techniques include sniffing the vapors that evolve from vaporized particles on a surface and wiping a surface followed by extraction and analysis of the wipe.

The sampling efficiency in the sniffing technique is dependent on the particle evaporation rate. For low volatility substances, heating may be required to enhance

the sampling efficiency. This is not desirable in many applications including examining luggage for explosives or drugs at airports.

The wiping method also has low sampling efficiency. This method cannot be used in many applications involving sensitive surfaces that can be damaged by wiping.

The present invention describes a new technique, which the inventors have titled Shock-Wave Enhanced Entrainment of Particles (SWEEP). This SWEEP technique uses shock waves to enhance the entrainment of small particles that adhere to a surface. A shock wave passing or reflecting from a surface creates an impulsively initiated fluid flow behind it that results in high shear near the surface. In addition, the shock wave pressurizes the fluid above the surface, thus generating a higher density. The combination of high density and high shear yields a high drag force on particles attached to the surface, thus promoting their entrainment.

This technique can be used for cleaning surfaces or detecting particles of a substance. Prototype SWEEP systems have been built utilizing the gas flow at the exit of a small shock tube to remove minute particles from a surface. A removal efficiency greater than 80% was observed in removing gravitationally deposited MgO powder with particles of less than 45mm in diameter after

a few shots with a Mach 1.5 shock.

One aspect of the present invention is techniques to improve and focus the efficiency in particle removal by the SWEEP technique. This is due to the careful matching of unique properties of the shock wave interacting with tenacious particles adhered on surfaces. The present invention allows sampling of a sufficient amount of a material for subsequent testing and detection from a very small amount of residue of a target substance on surfaces.

Another aspect of the SWEEP technique is the small amount of gas that is required to entrain bound particles from a surface. Other gas-jet based methods for particle entrainment require much larger gas flows, leading to undesirable dilution of the removed materials and limiting the ultimate sensitivity of a trace contaminant detection system. Since only a brief pulse of gas is required to generate the shock wave, the entrained particles are dispersed into a small flow and are much more concentrated when collected, leading to greater analytical sensitivity.

Yet another aspect of the invention is the use of the SWEEP technique to preserve the quality of the surfaces upon which shock waves are launched to remove small particles. The SWEEP technique allows removing tenacious particles on a surface without physical touching of the surface. This is desirable in

applications such as cleaning semiconductor wafers and non-invasive probing of explosives and drugs on sensitive surfaces.

Yet another aspect of the invention is the fast processing time inherent in the SWEEP technique. The high-speed shock wave traveling across a target surface allows nearly instantaneous entrainment of small adhered particles over a large area of a target surface.

Yet another aspect of the invention is to produce a system based on the SWEEP technique that is compact and energy efficient in comparison with many prior-art systems.

Yet another aspect of the invention is to use the heating effect of the shock to facilitate detection of particulate particles. The rise in local temperature as the shock passes increases the vaporization of the particles therein and thereby facilitates vapor detection. This shock heating may, if desired, be made sufficiently intense to ignite specific explosive particles that are lifted off a surface by the shock.

Yet another aspect of the invention is an enhanced detection efficiency by phase sensitive detection techniques in a detection system for probing explosive or contraband substances using the SWEEP technique.

The invention has versatile applications including, but not limited to, detecting explosive material, drugs and other contraband, cleaning surfaces

such as high-quality optical components and semiconductor wafers, and applications involving removal of minute particles from surfaces that are submerged in liquids or removal of particles from porous materials by using the SWEEP system in a transmission mode as described herein.

Brief Description of the Drawing

Figure 1 shows the relationship of the shock speed and fluid speed with the shock strength based on the one-dimensional postulation, respectively.

Figure 2 shows the heating effect caused by a shock wave as a function of the shock strength based on the one-dimensional postulation.

Figure 3 shows the burst diaphragm or valve pressure ratio versus generated shock strength.

Figure 4 illustrates a prototype SWEEP system for removing particles from a glass substrate.

Figure 5 shows the glass substrate with particles before the cleaning by firing six shock waves.

Figure 6 shows the glass substrate with particles after the cleaning by firing six shock waves.

Figure 7 shows measured particle removal efficiency versus number of gas puffs and shock waves that are fired.

Figure 8 shows measured particle removal efficiency per shock wave and per gas puff.

Figure 9a illustrates a SWEEP system having a

chemical analyzer for detecting and identifying explosive materials and other chemicals on a target surface.

Figure 9b illustrates a SWEEP system having a sorbent trap assembly for concentrating and detecting/identifying explosive materials and other chemicals on a target surface.

Figure 10 illustrates a SWEEP system for cleaning surfaces.

Figure 11 shows a block diagram of a phase-locked detection system in a SWEEP system.

Figure 12 illustrates a SWEEP system using transmission of shock waves for detecting and identifying explosive materials and other chemicals on a porous material.

Description of the Preferred Embodiments

The Shock-Wave Enhanced Entrainment of Particles (SWEEP) of the present embodiments utilize the impulsive thermodynamic and fluid mechanical changes that occur as a result of the passage of a shock wave in a fluid medium. The terminology "fluid" used herein is meant to include both gaseous media (e.g., air) and liquid media (e.g., water).

A shock wave is a thin region of rapid state variation (e.g., on the order of 10^{-6} m) that travels at a supersonic speed in a fluid. A shock wave is often viewed as a traveling discontinuity in the fluid state

since the fluid velocity, fluid pressure, fluid temperature and fluid density undergo a rapid change across the traveling thin region. It is possible to generate a shock wave in many different ways; in general, any rapid disturbance in the fluid velocity, fluid pressure, fluid temperature, or fluid density can produce a shock. Shock waves are characteristic of supersonic flows, since they can only occur when flow velocities exceed the acoustic velocity (sound speed). Detailed descriptions of shock waves can be found in the following literature which is incorporated by reference into this disclosure: "Compressible Fluid Dynamics" by Philip A. Thompson (The Maple Press Company, 1984); "Elements of Gasdynamics" by H.W. Liepmann and A. Roshko (John Wiley & Sons, Inc., 1957); and "Fundamentals of Gasdynamics" edited by H.W. Emmons (Princeton University Press, 1958).

In the SWEEP technique in accordance with the present invention, a shock wave that is generated and guided to pass over a surface produces an impulsive changes in the velocity, density, pressure and temperature. The rapid change in the fluid velocity results in a thin boundary layer that creates a region of high shear near a surface. In addition, the shock wave pressurizes the fluid as it passes, thus generating a higher density. The drag force acting on a particle of diameter D_p surrounded by a fluid of density ρ moving with

a uniform velocity u_∞ is expressed as the following according to Flagan and Seinfeld in "Fundamentals of Air Pollution Engineering", Prentice Hall, New Jersey, 1988:

$$F_{drag}=\frac{\pi}{8}\rho C_D D_p^2 u_\infty^2, (3)$$

where C_D represents the dimensionless drag coefficient. A particle attached to a surface will experience a drag force with similar dependence on the density, diameter, and velocity as equation (3). Therefore, the combination of high density and high velocity near the surface to which the particle is bound produced by the impulsive fluid acceleration as the shock wave sweeps over the surface yields a high drag force on the particle bound to the surface, thus promoting their removal and entrainment.

The inventors postulate a theoretical explanation of the invention in a simplified one-dimensional case for a better understanding of the underlying principles. The concept of the simplified one-dimensional theory can be expanded to further include the three-dimensional case. The validity of the postulation should not be bounded to the embodiments and their ramifications of the present invention. A brief account of the postulation is described as follows.

One-dimensional shock flow will be considered herein to illustrate the underlying concept. Additional information regarding the theory can be found in the following literature which is incorporated by reference in this specification: Phillip A. Thompson, "Compressible Fluid Dynamics", The Maple Press Company, 1984; Liepmann, H.W. and Roshko, A., "Elements of Gasdynamics", Wiley, New York, 1957. Effects of shock reflections from the surface are neglected herein. The strength of the shock wave is defined by the ratio of the pressure behind the shock, p_2, to the pressure ahead of the shock, p_1. The velocity of the flow behind the shock, u_2, the density ratio across the shock ρ_2/ρ_1, and the shock Mach Number M_1 can all be expressed in terms of this shock strength (assuming perfect gas):

$$u_2=c_1\left(\frac{p_2}{p_1}-1\right)\sqrt{\frac{2/\gamma_1}{(\gamma_1-1)+(\gamma_1+1)p_2/p_1}}, \quad (4)$$

$$\frac{\rho_2}{\rho_1}=\frac{(\gamma_1-1)+(\gamma_1+1)p_2/p_1}{(\gamma_1+1)+(\gamma_1-1)p_2/p_1}, \quad (5)$$

$$M_1=\frac{u_{shock}}{c_1}=\sqrt{\frac{(\gamma_1-1)+(\gamma_1+1)p_2/p_1}{2\gamma_1}}, \quad (6)$$

where c_1, γ_1, and ρ_1 represent the sound speed, the ratio of specific heats, and the density of the ambient fluid ahead of the shock, respectively; u_{shock} is the speed of the shock, and ρ_2 represents the density of the fluid behind the shock.

Plots of the dependence of the shock speed and the fluid speed on the shock strength are shown in Figure 1. Curves 100 and 102 show that the shock speed u_{shock} and the fluid speed u_2 increase with the shock strength p_2/p_1. Figure 1 also indicates that the speed of a shock wave is much higher than that of the fluid behind the shock wave but the fluid velocity is still high enough to exert a large aerodynamic drag force on the particle.

According to the above equations, a modest shock strength of p_2/p_1 =2.5 in air (γ_1 = 1.4; c_1 =343m/sec; ρ_1 =1.21 kg/m^3) yields a shock Mach number of 1.5 and generates a fluid velocity of u_2= 243 m/sec and a density of ρ_2 =2.3 kg/m^3 behind the shock. This Mach 1.5 shock travels at 515 m/sec (i.e., 515 mm/msec) with a boundary layer growing on the surface behind it as it travels. The fluid velocity ahead of the shock is essentially 0 m/sec and the fluid velocity behind the shock is 243 m/sec. The flow is impulsively accelerated within the thickness of the shock, which is less than 1 mm for shock Mach numbers in air of 1.2 or greater. This impulsive

start to the flow yields high shear near the surface due to the thin boundary layer. The large velocity and density provide positive contributions to the drag force that can be imposed on minute particles bound to the surface.

The inventors also realized that other aspects of shock-induced fluid flows can be used to detect explosive materials. Local heating is induced from the passage of a shock wave. The amount of shock-induced heating can be significant and is expressed in terms of the shock strength as follows:

$$\frac{T_2}{T_1}=\frac{(\gamma_1+1)+(\gamma_1-1)\,p_2/p_1}{(\gamma_1+1)+(\gamma_1-1)\,p_1/p_2},\ (7)$$

where T_1 and T_2 are the absolute temperature of the fluid ahead of and behind the shock wave, respectively. In Equation (7), the pressure ratio in the denominator is the inverse of the shock strength. For the same shock strength mentioned above, i.e., $p_2/p_1 = 2.5$, the temperature ratio across the shock would be 1.3, which would generate a temperature of 390K behind the shock, at ambient conditions. Figure 2 shows a plot of this temperature ratio as a function of the shock strength. Clearly, the heating effect increases with the shock strength p_2/p_1.

One embodiment of the present invention is shown in Figure 4. This is used to evaluate the SWEEP technique for particle removal. The objective was to produce shock waves, aim them at a particle laden surface, and evaluate their removal effectiveness. One convenient and traditional means of producing shock waves is to use a shock tube with a burst diaphragm separating a region of high pressure p_4 gas (driver gas) from a region of low pressure p_1 gas (driven gas); a shock is produced in the driven gas when the diaphragm is broken. The diaphragm pressure ratio p_4/p_1 necessary to produce a shock of a particular strength, is given by the following expression:

$$\frac{p_4}{p_1}=\frac{p_2}{p_1}\left[1-\frac{(\gamma_4-1)\,(c_1/c_4)\,(p_2/p_1-1)}{\sqrt{2\gamma_1}\sqrt{2\gamma_1+(\gamma_1+1)\,(p_2/p_1-1)}}\right]^{-\frac{2\gamma_4}{\gamma_4-1}} \quad (8)$$

where γ_4 *and* c_4 are the specific heat and sound speed associated with the high-pressure driver gas thereabove. A plot of this function in Equation (8) is shown in Figure 3. Curves 300 and 302 are computed for the case where air is the driver gas and the case where helium is the driver gas, respectively. In both cases, the driven gas is the air at ambient conditions. Clearly, the higher the diaphragm pressure ratio p_4/p_1, the stronger

the generated shock p_2/p_1. According to Figure 3, generation of a shock with a strength of 2.5 using air for both the driver gas and the driven gas requires a diaphragm pressure ratio of about 7.3, or a driver pressure of 730 kPa with ambient atmospheric conditions in the driven section. If helium were used as the driver gas, a shock strength of 2.5 could be generated with a diaphragm pressure ratio of only 3.8, or a driver pressure of 380 kPa.

Figure 4 shows the prototype apparatus used for this preliminary test of the SWEEP technique. A sample surface 402 is a glass substrate having MgO particles. The shock generator 400 has a shock tube 404, a burst diaphragm 406, a solenoid valve 408, and a high pressure gas source 420. A pressure gauge 410 monitors the high pressure p_4 of the driver gas at the valve 408. A flexible gas conduit 412 delivers the high pressure driver gas from the gas source 420 to the burst diaphragm 406. 414 is an optional gas filter and 416 is a gas regulator. 418 is a valve to turn on and off the high-pressure gas to the burst diaphragm 406.

The shock tube 404 can be made in various forms and from many materials. For example, a stainless steel cylindrical tube with an outer diameter of about 1/4" (6.4mm) and a length of about 12" (30.5cm) long can be used. The high pressure gas source 420 can be a gas tank with compressed pure gas like Nitrogen (e.g., at a

pressure of about 800kPa). The MgO powder on the sample surface 402 having a distribution of particle sizes with diameters less than 45 mm was deposited on the sample surface 402 by gravitational settling.

In operation, the valve 408 quickly opens for a short duration (e.g., 3-5 msec) and closes. This action generates a high pressure in the region between the diaphragm 406 and the valve 408 and thereby further causes bursting of the diaphragm 406. Thus, a shock wave is generated in the shock tube 404 and propagates towards the tube opening 403 and the sample surface 402. The opening 403 of the shock tube 404 was aimed at the sample surface 402 at an angle q. The particles on the sample surface 402 were detected by using a CCD camera 430 attached to a microscope 440 with a field of view of about 2 mm. In this configuration, 1 pixel width of the CCD camera corresponded to a distance of about 6 mm on the sample surface 402. The particles were illuminated at a glancing angle using a He-Ne laser at 632 nm (not shown). Dark-field microscopy was used so that adhered MgO particles appeared as bright spots on a dark background. Images were recorded before and after each shock was fired at the sample surface 402.

The dark-field microscopy images were processed using a commercially available software package. The grey scale images were sharpened and inverted. A

threshold was set at a fixed value to produce a binary image. The particles on the glass substrate were then counted using a particle identification algorithm built into the program.

Figure 5 shows the initial particle distribution on the sample surface 402 captured by the CCD camera 430 prior to firing any shocks. Figure 6 shows the final particle distribution after firing 6 shocks at the sample surface 402 with the angle q at 30°. It is clear from these images that the SWEEP technique removes the particles quite readily from the sample surface 402. There was an apparent misalignment between the particles that remain in the field of view after the sixth shock was fired compared to the location of particles in the initial image; this is likely due to particles moving within the field of view or particles being redeposited from the region of the surface upstream of the field of view.

The number of particles removed by each shock was determined by identifying and counting the particles before and after each shock was fired. In addition, by taking the ratio of the number of remaining particles to the number of initial particles, the overall removal efficiency and the removal efficiency per shot was calculated. The results are summarized in the two plots shown in Figures 7 and 8.

It is clear from the measurements represented by curve 700 in Figure 7, that greater than 80% removal can be obtained with only six shots from the shock generator 400. The plot of removal efficiency per shock wave is represented by curve 800 in Figure 8. It shows that the percentage removal does not change significantly from shot to shot after the first one. The first shot has higher removal yield (more than 45% in removal efficiency per shot) than the subsequent shots. This is probably because the first shot removes many particles that may not be tightly bound to the surface. One exception on the third shot #3 is likely due to a misalignment of the shock tube with the viewing area. The removal efficiency also drops off near the end of the series, perhaps at least in part due to the dramatic reduction in the number of particles on the surface that leads to reduced statistics.

The inventors also measured the removal efficiency of gas puffs in comparison with the shock waves. Gas puffs were launched at the surface 402 using the same shock tube setup without the burst diaphragm 406. As indicated by curve 702 of Figure 7 and curve 802 of Figure 8, after the first puff, no significant removal was observed even after four puffs. After completing these four puffs, a burst diaphragm was loaded into the same apparatus and a shock wave was fired at the same sample. Almost half of the particles that remained after

four gas puffs were removed by the first shock wave. Subsequent firing of the shocks removed even more material up to over 80% after 6 shots. It is clear from these measurements that gas puffs and the shock waves are very different in their physical characteristics and in their particle removing capability.

A shock wave is a traveling discontinuity that creates a sudden step spatial and temporal change in the gas velocity, gas pressure, gas temperature, and gas density. The shock wave travels at a supersonic speed across the surface. At a typical Mach Number of 1.5, the shock wave is traveling approximately at 515 m/sec. The interface between the high and low pressure gases that creates the shock (e.g., at the burst diaphragm or fast valve) is left far behind and travels at the gas velocity of about 243 m/sec in the example of the Mach Number 1.5 shock.

A gas puff on the other hand creates a startup vortex at the tube exit that scours the surface generating a rapid, but not discontinuous change in the gas velocity near the surface. A gas puff is not a traveling discontinuity, and a shock wave is not generated by the puff.

In the tests, both the gas puffs and the shock waves were created with the same gas pressure from the gas source 420 using the prototype system shown in Figure 4. A burst diaphragm 406 was needed in combination with

a slow valve 408 to create the shock waves while the gas puffs were generated with the slow valve 408 alone.

Bursting of a diaphragm 406 is used to generate a shock in the above described prototype SWEEP device 400. The burst diaphragm 406 can be made from various materials such as metal, plastic, rubber, etc. The diaphragm 406 and the valve 408 separate the high-pressure reservoir from the shock tube 404 and provide a fast open-close action to generate a shock.

Although a solenoid valve 408 and a burst diaphragm 406 were used in the prototype shown in Figure 4, there are fast valves that can be used without a burst diaphragm to generate shock waves. For example, the inventors also used an Induced Eddy Current (IEC) valve to replace the diaphragm 406 and the solenoid valve 408 in the SWEEP system shown in Figure 4 for generating shock waves. An IEC valve uses a large pulsed current with a duration in an order of 40ms to open the valve, which is usually fast enough to generate a shock wave. Other examples of such fast valves include, but are not limited to, pneumatic valves, electromagnetic valves, mechanical valves based on a spring-latch or rotating spring-latch cam for repetitive shocks, piezo-electric valves, bistable diaphragms having stable open and close states and a fast switching mechanism between the two states.

The following literature is incorporated herewith by reference to provide additional information regarding many aspects of the above-listed valves that can be used in practicing the present invention:

IEC valve: Gorowitz et al., "Magnetically driven fast-acting valve for gas injection into high vacua", Rev. Sci. Instrum., Vol 31, No. 2, pp146-148 (1960), Prut and Shibaev, "An injector of solid hydrogen pellets", Instruments and Experimental Techniques, Vol. 37, No. 2, Part 2, pp95-199 (1994);

Pneumatic valve: Hurst and Bauer, "A piston-actuated shock-tube with laser-Schlieren diagnostics", Rev. Sci. Instrum., Vol 64, No. 5, pp1342-1346 (1993);

Electromagnetic valve: Fleurier et al., "Fast valve for ion beam-plasma interaction", Nuclear Instruments and Methods in Physics Research, B61, pp236-238 (1991);

Piezoelectric valve: Bates and Burrell, "Fast gas injection system for plasma physics experiments", Rev. Sci. Instrum., Vol. 55, No. 6, pp934-939 (1984);and

Mechanical spring latch valve: Kim, "A new, diaphragmless, flexible, luminous shock tube", in "Shock Tubes and Waves: Proceedings of the 13th International Symposium on Shock Tubes and Waves, Niagra Falls, State University of New York Press, pp89-97 (1981).

Other methods for generating shock waves are

contemplated in accordance with the present invention. Some examples include: spark discharge in gas ionization and flash vaporization of liquids, laser discharge in gas ionization and flash vaporization of liquids, explosion by a chemical reaction, piston moving in a shock tube (e.g., driven by a motor/cam for repetitive shocks). Some aspects of these techniques can be found in the above-referenced literature of "Compressible Fluid Dynamics" by Philip A. Thompson. However, some methods may be better suited for sampling rather than cleaning if the shock generators produce additional particles.

In addition, shocks can be directed to a surface through shock tubes of various shapes depending on the specific applications such as square, rectangular, circular, oval, etc. This is possible because a shock wave stabilizes to the tube shape quickly.

It is also feasible to eliminate the shock tube and perhaps use a parabolic reflector to direct the shock at a target surface from a shock generator placed at the focus of the parabola. In particular, the inventors of the present invention contemplate the use of a shock-wave reflector and a laser/spark induced plasma in combination to produce and guide shock waves. Another possibility is to leave the shock wave unguided, thus allowing it to proceed outward in a spherical pattern from the generation point. This method can be used to collect particles over a circular region by providing

circumferential collection with a shock generator at the center that is positioned near the target surface.

Furthermore, guiding elements can be designed in the SWEEP device to focus or defocus a shock wave for specific applications. In focusing a shock wave, the shock strength is increased. On the other hand, defocusing a shock wave can be used to increase the area of a target surface that is affected by the shock wave.

The SWEEP technique could be utilized in a number of devices that are used to remove particles from a surface and entrain them into an gas stream. For example, the SWEEP technique can be used in a cleaning system that removes particulate contaminants from the surface of semiconductor materials prior to etching of features to increase product yield, or a detection device that samples particles from the surface of luggage to detect the possible presence of explosives or drugs, or an optical cleaning device that removes contaminants from the surface of high-power laser optics to decrease the optical absorption and thus increase the laser damage threshold.

A detection instrument that combines the SWEEP technique with an analytical detector can be used for the detection and/or identification of low volatility chemicals including explosive materials. Such a chemical detection system can also be used for detection of drugs and other contraband substances. Figure 9a shows a

schematic of such a detection instrument in accordance with the present invention. A shock wave generator 902 produces and delivers shock waves to a target surface 904 having various types of minute particles adhered thereon to be detected or identified. A suction unit 906 provides an air flow to lead and entrain particles from the target surface 904 to the detection system. This can be done by generating a lower pressure in the suction unit 906 than the ambient pressure near the target surface 904 and thus the air is drawn into the suction unit 906 along with the particles. A heater 920 heats the gas stream to vaporize the entrained particles from the target surface 904. An analyzer 922 is used to detect and identify the chemical composition of the particles with high sensitivity, selectivity, and specificity.

The heater 920 in Figure 9a can be replaced by other devices for heating the sampled particles. For example, an infrared thermal source can be used to heat particles/fluid by thermal radiation; a heated gas stream that mixes with the entrained particle stream to heat thereof; a heating grid across the tube flow wherein the fluid heats by thermal diffusion and mixing of the hot fluid that contacts the grid with the cooler fluid that has passed through the holes in the grid (also, particles may flash vaporize/burn if they impact the grid as they pass), and a filter may be installed on the heated grid

to capture entrained particles and ensure that sufficient time is allowed for efficient vaporization of the suspect material, thereby facilitating efficient detection of the particulate material using detectors that respond to the vapor phase; Laser Pulse Heating of a region of the fluid; Selective heating and vaporization that selectively heats suspect materials by a particular wavelength of light or a radio frequency wave; passing the particle ridden sample stream through a flame front (blue flame) and watching for light flashes from the particles as they pass through the front.

A SWEEP detection system can also first charge the entrained particle stream and attract the removed particles to a deposition surface or fine grid by means of an applied electric field. The deposition surface or grid is then rapidly heated to quickly vaporize the attached particles for downstream detection and identification.

The chemical analysis can be augmented with a secondary flow for some applications. In one scenario, a high volumetric flow would be used to convey entrained particles to a filter or other particle capture device. After the surface in question has been thoroughly scanned, the sampling flow would be turned off, and replaced with a smaller flow that would convey vapors released upon heating to a detector that is sensitive to the vapor phase material. In another scenario, the

second flow could induce reactants or indicators that could be used to identify the removed substance.

A number of processing possibilities exist in such a SWEEP system once the particles have been entrained from a target surface. For example, mass spectrometry can be incorporated into a SWEEP system including sector mass spectrometry, quadrupole mass spectrometry, time of flight mass spectrometry, ion trap mass spectrometry, and Fourier transformation cyclotron resonance mass spectrometry. Moreover, a SWEEP system can combine the ion mobility spectrometry or gas chromatography to form a sensitive chemical analyzer.

It may also be possible to ascertain the presence or absence of explosive materials taking advantage of the tendency of explosive materials to ignite at much lower temperatures than most other materials. By heating explosive particles by any of the aforementioned means to a temperature at which the explosive material will ignite but other materials will not, the explosive materials may be detected by observing the light flashes that result when they burn. A detailed account of this detection technique is disclosed by Funsten, H.O. and McComas, D.J. in "Apparatus and method for detection of explosives residue using the optical deflagration signature", Internal Publication LANL 1995, which is incorporated herein by reference. Limited chemical information as to the nature of the burning materials may be obtained by

observing the emission wavelengths. Also, flame photometric spectrometry can be integrated with the SWEEP technique, especially pulsed flame photometric spectrometry, to provide elemental analysis.

Figure 9b shows another SWEEP system using a sorbent trap 936. At first, the system valves 924 and 926 are configured so that the sampled particles and vapors are collected on the sorbent trap 936 and do not pass through the analyzer 922. The system is subsequently reconfigured with valves 924 and 926 so that the sampled particles and vapors can be rapidly desorbed into an analytical carrier gas by rapid heating. The carrier gas brings the particles and the vapors to the analyzer 922 for identification. This increases the concentration and allows integrated analysis of the materials extracted from a single object. Alternatively, the particles could be collected on a filter and then pulse vaporized for analysis. Yet another variant would be to collect the particles and vapors on a combination of a filter and a sorbent trap to ensure efficient collection regardless of the phase in which the material reaches the trap system. The collected vapor/particles could then be pulse-desorbed/vaporized for analysis.

If particle removal is the only concern of a particular application, then the need for downstream analysis/detection instrumentation may be eliminated. A SWEEP system for cleaning surfaces is shown in Figure 10.

Particles bound to a target surface 904 are first removed by the SWEEP technique using a shock wave generator. The entrained particles are then directed from the surface 904 in a cleansing flow provided by a suction unit 906 and dumped into an exhaust 916. An optional imaging system 1002 can be implemented to monitor the target surface 904. This allows examination of the contamination on the target surface 904 including quantitative information on contaminant particles (e.g., number and size of particles).

A cleaning system can also utilize downstream detection instrumentation for monitoring the target surfaces. For example, in some applications, it might be desirable to observe the collected particles and continue cleaning until the number or size of collected particles drops below a certain threshold value. In some cases, it may not be feasible to observe the surface being cleaned and the downstream analysis may be the only evidence that cleaning is being accomplished.

In the above SWEEP systems, particles can be collected by any means feasible after removal from a surface using the shock waves. In preferred embodiments, a cleansing flow is generated to entrain the particles removed by shock waves from a target surface. One method to generate such a cleansing flow is by suction, which creates a flow in the fluid as described herebefore. Another method to generate a cleansing flow is shown in

Figure 4, wherein the high pressure gas flow that is used to generate the shock wave by bursting a diaphragm serves as the cleansing flow to entrain the particles. Also, a low-speed gas flow such as nitrogen gas can be used to "blow" over the surface and entrain the particles that are removed by the shock waves.

Other means of collecting the removed particles can be used in a SWEEP system. For example, magnetic devices can be used to collect ferromagnetic particles that are removed from a surface by the SWEEP technique. Also, an electromagnetic field can be used for trapping and collecting of charged particles. For example, an electric field can be imposed so the charge transfer is induced as the particles are separated from the surface.

The heating effect caused by shock waves may be useful in analyzing and detecting particular chemical components in the entrained particles by the SWEEP technique. The pressure and fluid density discontinuities operate in combination to remove small tenacious particles from a surface. The heating of particles by the shock waves increases the evaporation rate and thus further promotes material removal. In sampling a low volatility substance, this shock-induced heating can further enhance the sampling efficiency of a sampling system using the SWEEP technique.

Another unique feature of a SWEEP system for chemical analysis is the high detection sensitivity.

This is desirable in detecting a very small amount of residual particles from a particulate chemical substance. As described previously, a SWEEP system is efficient at removing particles from a target surface. This contributes to the high detection sensitivity of the SWEEP system. A SWEEP system can further enhance the detection sensitivity by using phase-sensitive detection. A mechanism for phase-sensitive detection is inherent in the SWEEP system. Shock waves are discontinuous and a SWEEP system can generate shock waves at a fixed repetition rate or shock-wave firing frequency. This allows phase locking the detection system to the shock-wave firing frequency. Figure 11 illustrates this feature in a SWEEP detection system.

The SWEEP technique shows promise as a viable means of particle removal from surfaces. The implementation of this technique into an instrument for the removal of particles to detect and identify low volatility compounds has distinct benefits. Due to the use of shock waves as the means for particle removal, the amount of gas supply required for the particle removal process would be small compared to that of a continuous jet. In fact, if a moving piston arrangement is used to generate the shock waves, a SWEEP system requires only the ambient air as the gas supply. The SWEEP technique also eliminates the additional complication of having to generate and add particles to a jet flow and does away

with the need for a high-powered laser. A cleansing air stream, that carries the removed particles to the analyzer could be produced using a small vacuum source; this would also help to alleviate any recontamination of the sample area.

Recent developments in the miniaturization of detection and analysis systems of create the possibility of producing a compact instrument for the security industry. The particle laden air stream, produced using the SWEEP technique, could be heated and analyzed to determine the presence of explosive materials. This type of detection instrument could be very compact, precise, and inexpensive, thus leading to a very viable instrument.

In summary, the present invention describes a novel Shock-Wave Enhanced Entrainment of Particles (SWEEP) method that uses shock waves for entrainment of minute particles adhered to a surface. This SWEEP technique can be used for cleaning surfaces or detecting and identifying particles of a particulate substance. A shock wave passing or reflecting from a surface creates an impulsively started flow behind it that results in high shear near the surface. In addition, the shock pressurizes the fluid above the surface, thus generating a higher density. The combination of high density and high shear yields high drag on particles attached to the surface, thus promoting their entrainment.

In particular, the above SWEEP systems for both on-line chemical analysis and explosive detection can be used in airports or airplanes to examine luggage or passengers for explosive materials or contraband substances. The high collection efficiency, fast processing speed, and surface-preserving properties inherent in the SWEEP systems are particularly beneficial in these applications.

Although the present invention has been described in detail with reference to a number of particular embodiments, one ordinarily skilled in the art to which this invention pertains will appreciate that various modifications and enhancements may be made without departing from the spirit and scope of the invention. For example, the present invention can be applied to liquid media. This includes using the SWEEP technique to generate shock waves in liquids for removing particles from submerged surfaces. For example, the SWEEP technique can be used in the cleaning of boat hulls, or the detection of soluble residues on underwater wreckage such as aircraft.

Another example of using the SWEEP technique is a SWEEP system in a transmission mode, as shown in Figure 12. This system is useful for sampling particles from a piece of porous material 1202. A shock-wave generator 902 and a suction device 906 are disposed relative to each other and located on opposite sides of the porous

material 1202. The shock wave generator 902 fires shock waves which impinge on the porous material 1202 and transmit therethrough. The shock waves interact with the laden particles to release the particles from the porous material 1202. The suction device 906 on the opposite side operates to collect the released particles and transport the particles to a chemical analyzer 922. This system can be used to check the fabrics on airplane seats or clothing for the presence of various materials.

All these and other and ramifications and modifications are intended to be encompassed within the following claims.

What is claimed is:

1. A system for removing particles from a surface in a fluid, comprising:

a shock-wave generator, operating to generate shock waves in said fluid;

a shock-wave delivering element, operating to guide said shock waves to said surface, said shock waves producing a force on said particles and thereby removing said particles from said surface; and

a particle entraining device, operating to generate a cleansing flow in said fluid in a vicinity of said surface, said cleansing flow entraining said particles that are removed from said surface by said shock waves.

2. A system as in claim 1, further comprising a monitoring device, operating to obtain information indicative of said particles that are adhered to said surface.

3. A system as in claim 2, wherein said monitoring device is an imaging device.

4. A system as in claim 2, wherein said information includes quantity, dimension, and location of said particles that adhere to said surface.

5. A system as in claim 1, wherein said entraining device generates said cleansing flow by suction.

6. A system as in claim 1, wherein said entraining device generates said cleansing flow by using a second fluid flow over said surface.

7. A system as in claim 1, wherein said entraining device further includes an electromagnetic element that collects said particles with an electromagnetic field after said particles are removed from said surface.

8. A system as in claim 1, wherein said fluid is a gaseous medium.

9. A system as in claim 8, wherein said gaseous medium is air.

10. A system as in claim 1, wherein said fluid is a liquid.

11. A system for overcoming adhesion of a particle on a surface in a fluid, comprising:

a fluid disturbing device, operating to produce a spatially confined disturbance in said fluid;

said disturbance traveling in said fluid at a supersonic speed;

a guiding element, guiding said disturbance to said particles attached to said surface at a predetermined angle with respect to said surface;

said disturbance creating a discontinuity in said fluid in a vicinity of said particle adhering to said surface; and

said discontinuity generating a removal force on said particle against said adhesion between said particle and said surface.

12. A system as in claim 11, wherein said discontinuity in said fluid caused by said disturbance includes discontinuity in fluid speed, fluid pressure, fluid temperature, and fluid density.

13. A chemical analyzer for detecting particles of a chemical substance on a surface, comprising:

a sampling device having a shock-wave generator and a particle collecting element, said shock-wave generator producing shock waves onto said surface;

said shock waves interacting with surrounding of said particles on said surface and creating a high shear at said particles, said high shear producing a dragging force to remove said particles from said surface;

said particle collecting element operating to collect said particles that are removed from said surface and to keep said particles from recombining with said surface;

a detecting device and an output terminal;

a particle conduit, disposed to connect said sampling device and said detecting device, operating to guide said particles from said sampling device to said detecting device; and

said detecting device, obtaining information indicative of said chemical substance from said particles, said output terminal displaying said information.

14. A chemical analyzer as in claim 13, wherein said shock-wave generator has a compressed fluid source, a valve and a diaphragm, which operate in combination to generate shock waves by bursting said diaphragm.

15. A chemical analyzer as in claim 14, wherein said diaphragm is made of metal.

16. A chemical analyzer as in claim 14, wherein said diaphragm is made of a plastic material.

17. A chemical analyzer as in claim 14, wherein said diaphragm is made of rubber.

18. A chemical analyzer as in claim 13, wherein said shock-wave generator has a pneumatic valve.

19. A chemical analyzer as in claim 13, wherein said shock-wave generator has an electromagnetic valve.

20. A chemical analyzer as in claim 13, wherein said shock-wave generator has a mechanical valve with a spring-latch therein.

21. A chemical analyzer as in claim 13, wherein said shock-wave generator has a piezo-electric valve.

22. A chemical analyzer as in claim 13, wherein said shock-wave generator has a mechanical valve with a motor-driven cam.

23. A chemical analyzer as in claim 13, wherein said shock-wave generator has a bistable diaphragm.

24. A chemical analyzer as in claim 13, wherein said shock-wave generator has a piston-type mechanical compression device.

25. A chemical analyzer as in claim 13, wherein said shock-wave generator has a laser discharge device or an electrical discharge device, operating to induce

discharging sparks and thereby to generate said shock waves.

26. A chemical analyzer as in claim 13, wherein said shock-wave generator has a chemical device that produces said shock waves by inducing explosive chemical reactions.

27. A chemical analyzer as in claim 13, wherein said shock-wave generator has a shock tube to guide said shock waves to said surface.

28. A chemical analyzer as in claim 13, wherein said shock-wave generator has a reflector to direct said shock waves to said surface.

29. A chemical analyzer as in claim 13, wherein said shock waves are initiated by said shock-wave generator at a generation point, said shock waves propagating outwardly with a spherical wavefront, thus allowing circumferential collection of said particles.

30. A chemical analyzer as in claim 13, wherein said shock-wave generator further includes a guiding device that can focus said shock waves.

31. A chemical analyzer as in claim 13, wherein

said particle collecting device produces a suction flow across said surface to entrain said particles that are removed from said surface by said shock waves.

32. A chemical analyzer as in claim 13, wherein said particle collecting device uses a magnetic force to collect said particles that are ferromagnetic.

33. A chemical analyzer as in claim 13, wherein said particle collecting device produces an electromagnetic field to collect said particles that are electrically charged.

34. A chemical analyzer as in claim 13, wherein said detecting device has a mass spectrometer to identify said chemical substance.

35. A chemical analyzer as in claim 34, wherein said mass spectrometer is selected from a group consisting of sector mass spectrometry, quadrupole mass spectrometry, time of flight mass spectrometry, ion trap mass spectrometry, and Fourier transformation cyclotron resonance mass spectrometry.

36. A chemical analyzer as in claim 13, wherein said detecting device further has an ion mobility spectrometry device to identify said chemical substance.

37. A chemical analyzer as in claim 13, wherein said detecting device further has a gas chromatography device to identify said chemical substance.

38. A chemical analyzer as in claim 13, wherein said detecting device has a heating element to ignite said particles obtained from said sampling device and a photodetector to receive light emission from said particles for retrieving a deflagration signature indicative of said chemical substance.

39. A chemical analyzer as in claim 38, wherein said deflagration signature is the wavelength of said light emission.

40. A chemical analyzer as in claim 38, wherein said deflagration signature is temperature.

41. A chemical analyzer as in claim 38, wherein said detecting device measures intensity of said light emission from said particles in time domain.

42. A chemical analyzer as in claim 38, wherein said heating element generates a hot gas stream to deflagrate or evaporate said particles.

43. A chemical analyzer as in claim 38, wherein

said heating element generates a thermal radiation to deflagrate or evaporate said particles.

44. A chemical analyzer as in claim 13, wherein said shock-wave generator produces said shock waves repetitively at a predetermined frequency and said detecting device has a means to phase lock a detected signal at said predetermined frequency.

45. A chemical analyzer as in claim 13, wherein said chemical substance is an explosive material.

46. A chemical analyzer as in claim 13, wherein said chemical substance is a drug.

47. A chemical analyzer as in claim 13, wherein said surface is a part of a porous material, allowing transmission of said shock waves and said shock-wave generator and said particle collecting element are arranged relative to each other so that said shock-wave generator is disposed on a first side of said surface of said porous material and said particle collecting element is disposed on a second side of said porous material, said second side opposing said first side.

48. A chemical analyzer as in claim 13, wherein said detecting device has a heating element to evaporate

said particles obtained from said sampling device.

49. A method of removing particles from a surface in a fluid, comprising:

generating a localized disturbance in said liquid; said localized disturbance traveling in said liquid at a supersonic speed;

directing said localized disturbance to said particles attached to said surface at a predetermined angle with respect to said surface, said localized disturbance creating a discontinuity in fluid speed, fluid pressure, fluid temperature, and fluid density of said fluid in a vicinity of said particles;

said discontinuity generating a dragging force on said particles to overcome binding force between said particle and said surface;

keeping said particles from recombining with said surface; and

entraining said particles from said surface.

50. A method of detecting and identifying presence of a substance on a surface, comprising:

generating shock-waves and directing said shock waves onto said surface having particles of said substance;

said shock waves interacting with surrounding of said particles on said surface and producing a

dragging force to remove said particles from said surface;

collecting said particles that are removed from said surface by said shock waves; and

analyzing said particles and obtaining information indicative of said substance.

FIG. 1

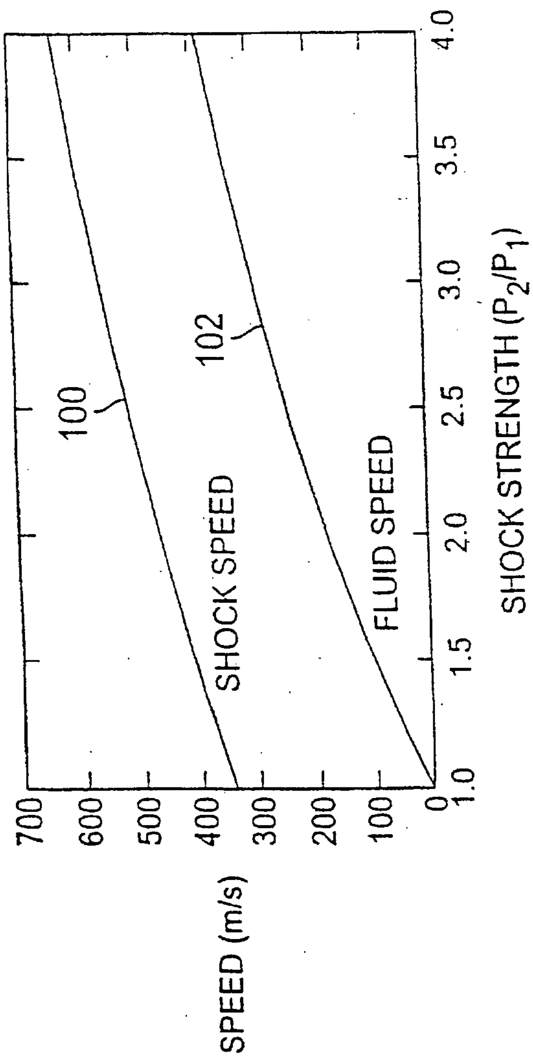

SPEED (m/s)
700
600
500
400
300
200
100
0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
SHOCK STRENGTH (P_2/P_1)
100
102
SHOCK SPEED
FLUID SPEED

FIG. 2

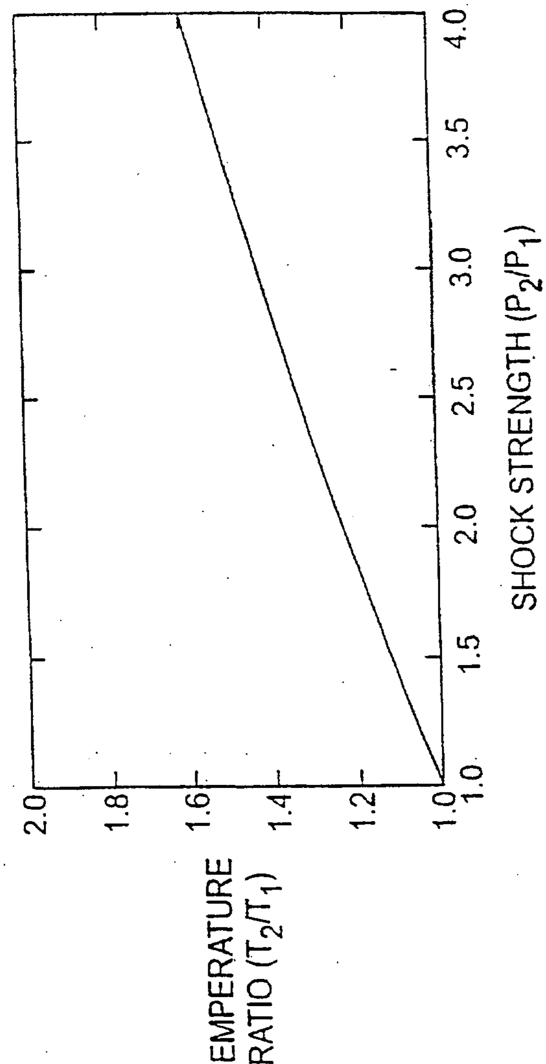
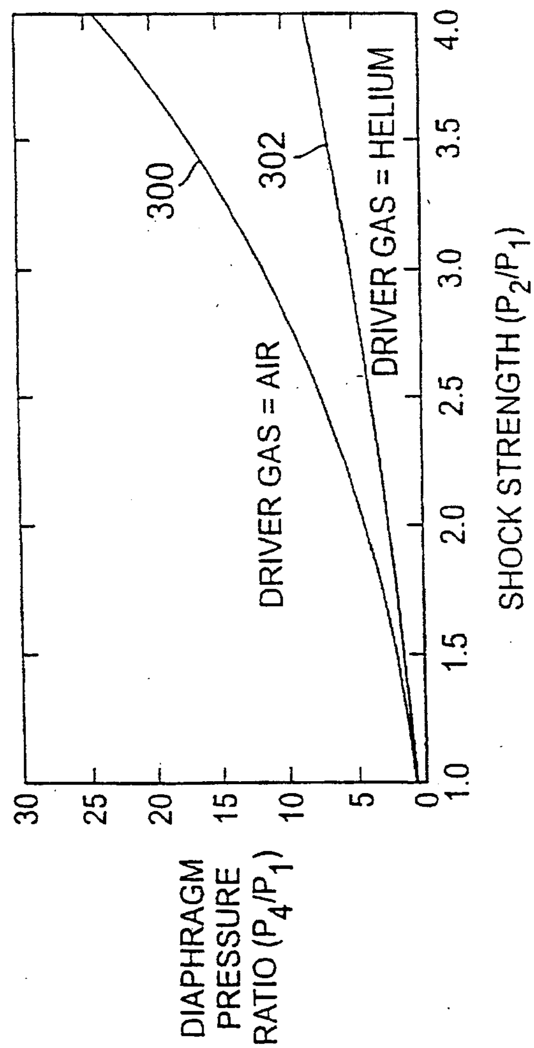

TEMPERATURE
RATIO (T_2/T_1)
2.0
1.8
1.6
1.4
1.2
1.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
SHOCK STRENGTH (P_2/P_1)

FIG. 3


300
302
DRIVER GAS = AIR
DRIVER GAS = HELIUM
DIAPHRAGM PRESSURE RATIO (P_4/P_1)
0
5
10
15
20
25
30
1.0
1.5
2.0
2.5
3.0
3.5
4.0
SHOCK STRENGTH (P_2/P_1)

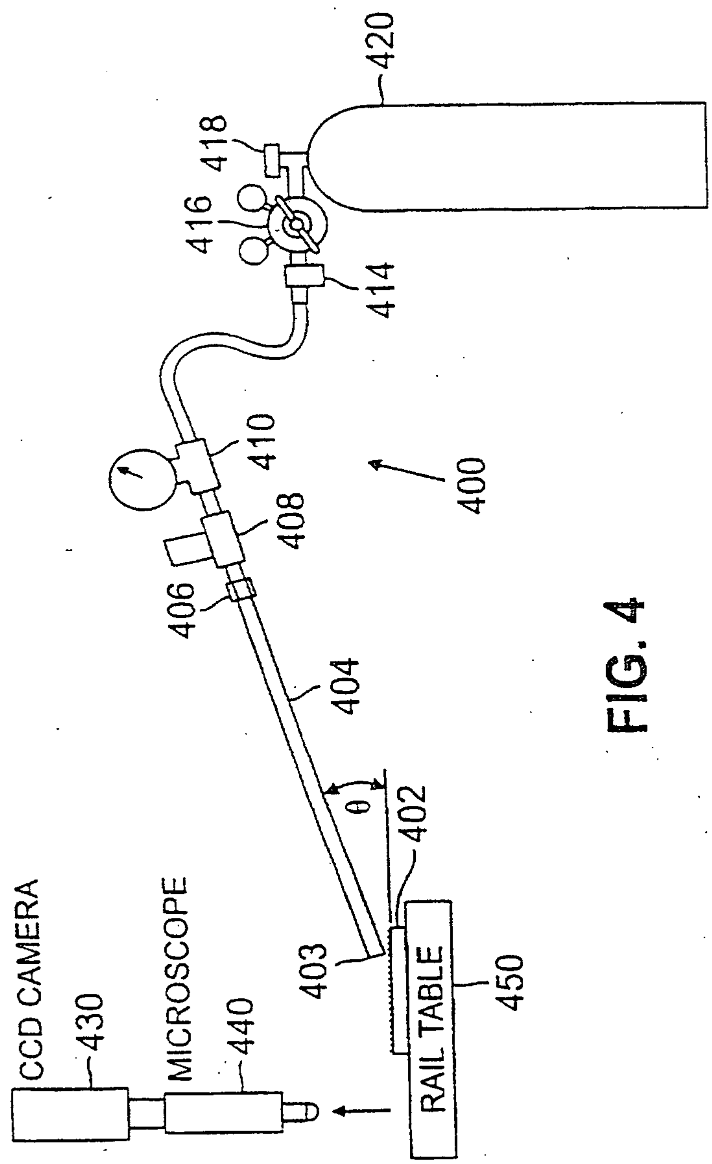

420
418
416
414
410
400
408
406
404
θ
402
403
RAIL TABLE
450
CCD CAMERA
430
MICROSCOPE
440

FIG. 4

INITIAL PARTICLE DISTRIBUTION

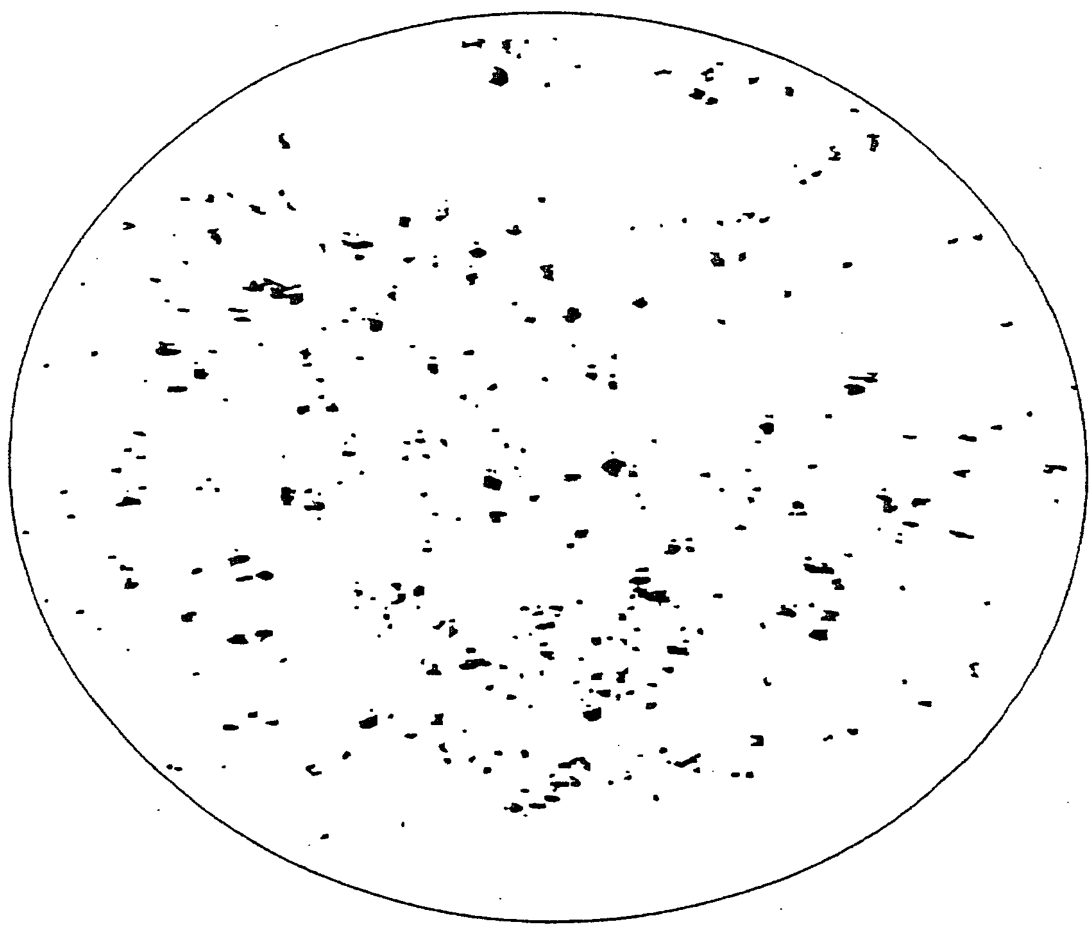


FIG. 5

FINAL PARTICLE DISTRIBUTION
AFTER SIX SHOCKS

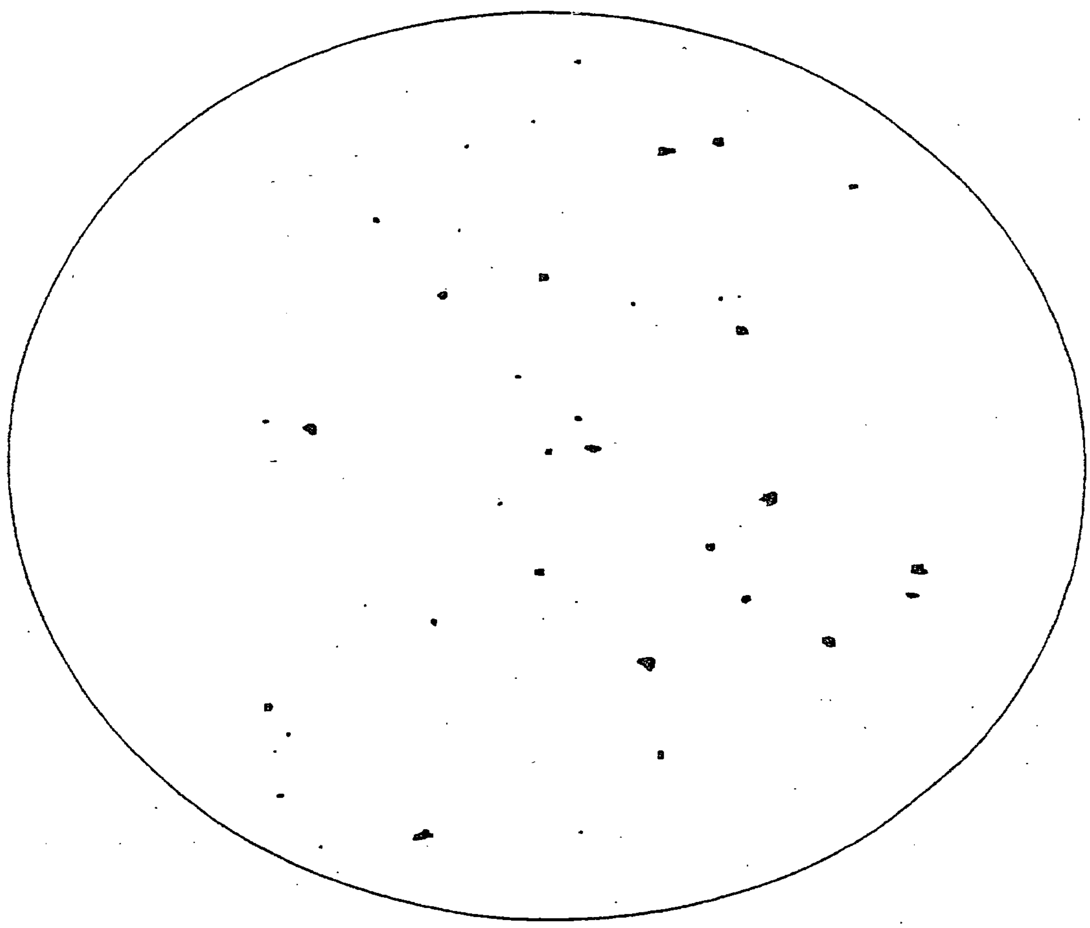


FIG. 6

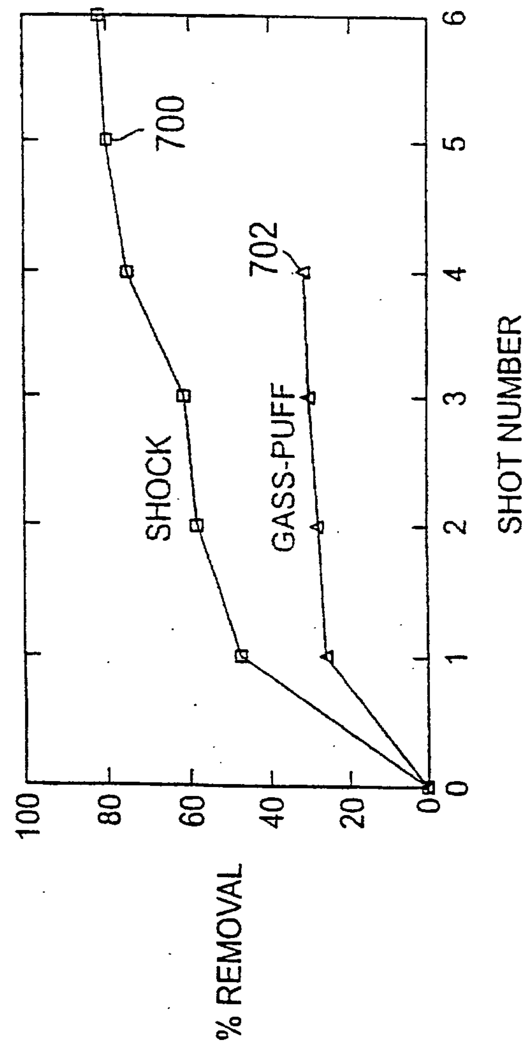

% REMOVAL
SHOT NUMBER
SHOCK
GASS-PUFF
700
702
100
80
60
40
20
0
1
2
3
4
5
6

FIG. 7

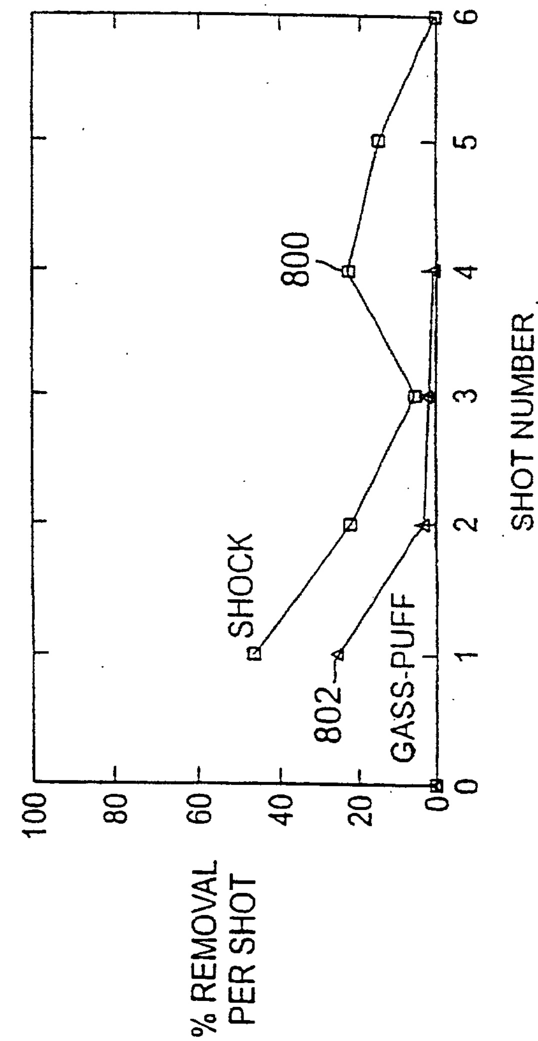

% REMOVAL PER SHOT
SHOT NUMBER
SHOCK
GASS-PUFF
800
802
100
80
60
40
20
0
1
2
3
4
5
6

FIG. 8

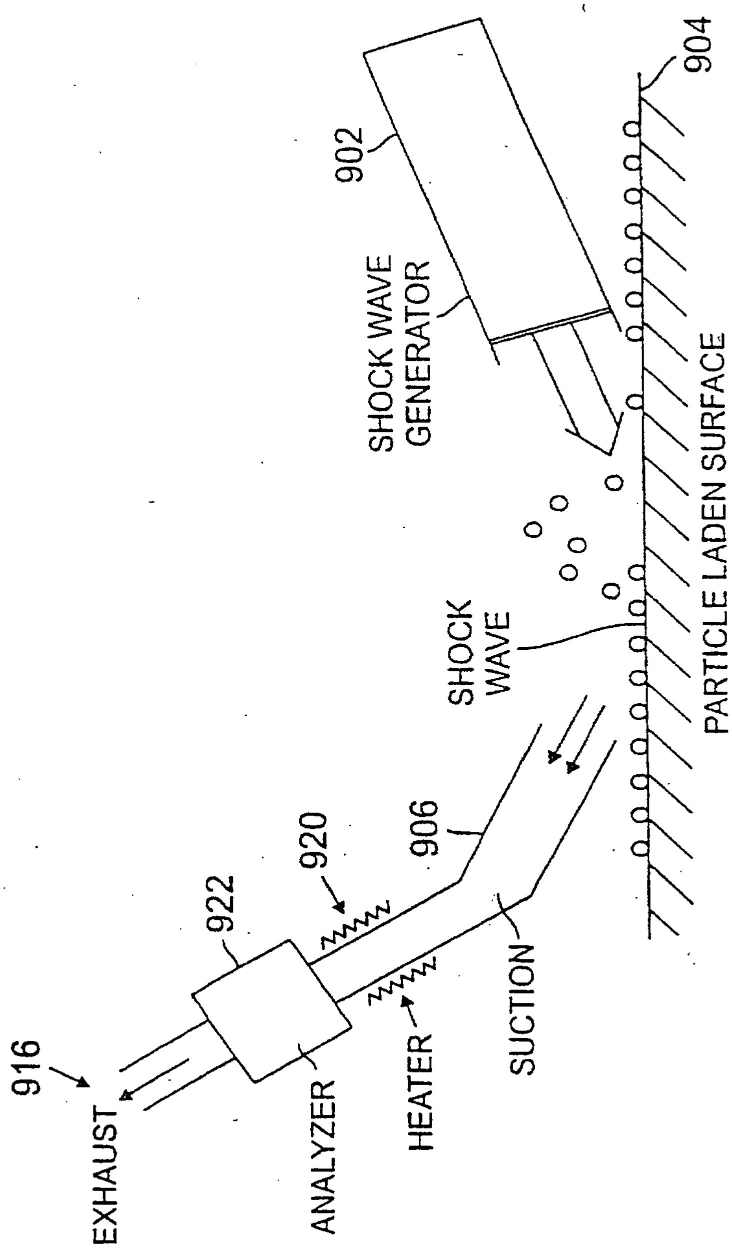

902
904
SHOCK WAVE GENERATOR
SHOCK WAVE
PARTICLE LADEN SURFACE
906
920
922
916
EXHAUST
ANALYZER
HEATER
SUCTION

FIG. 9a

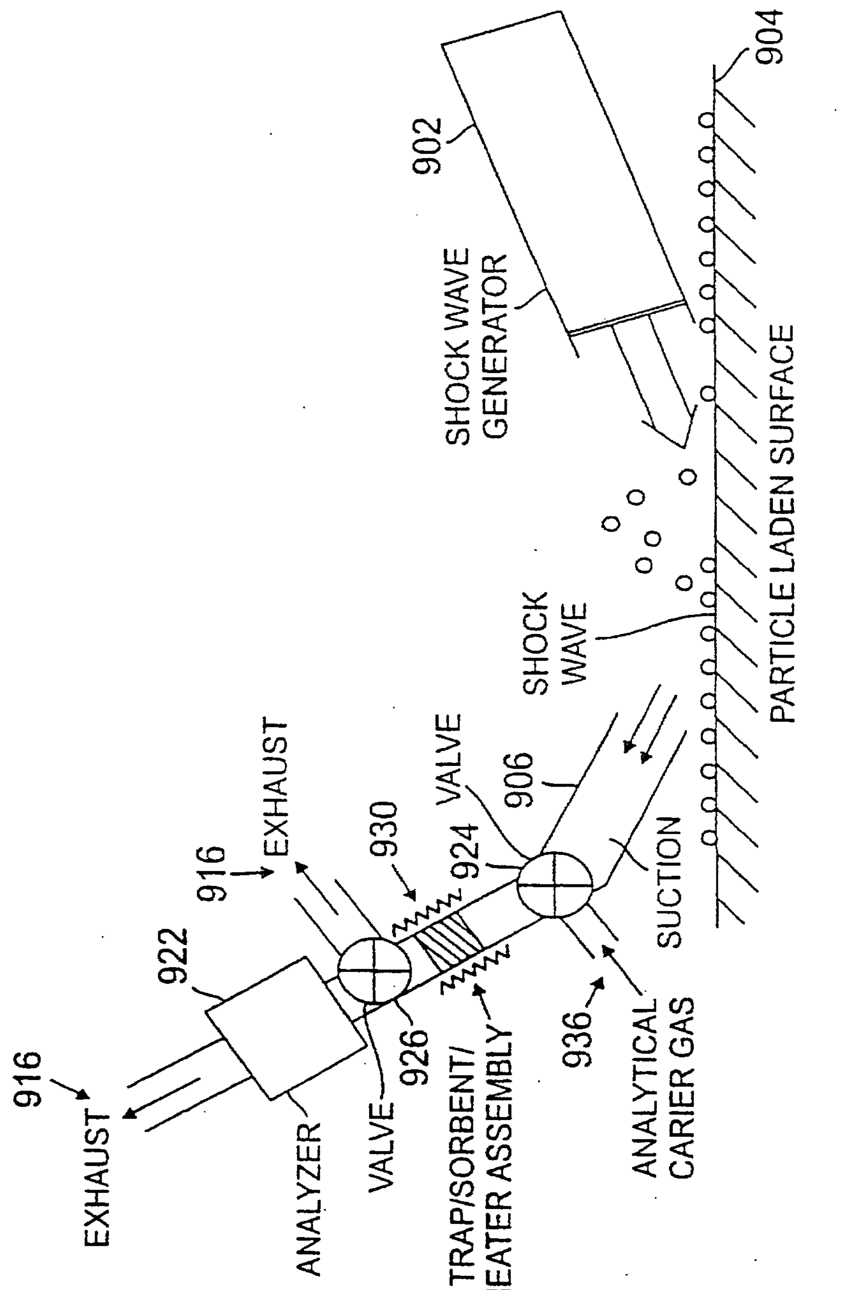
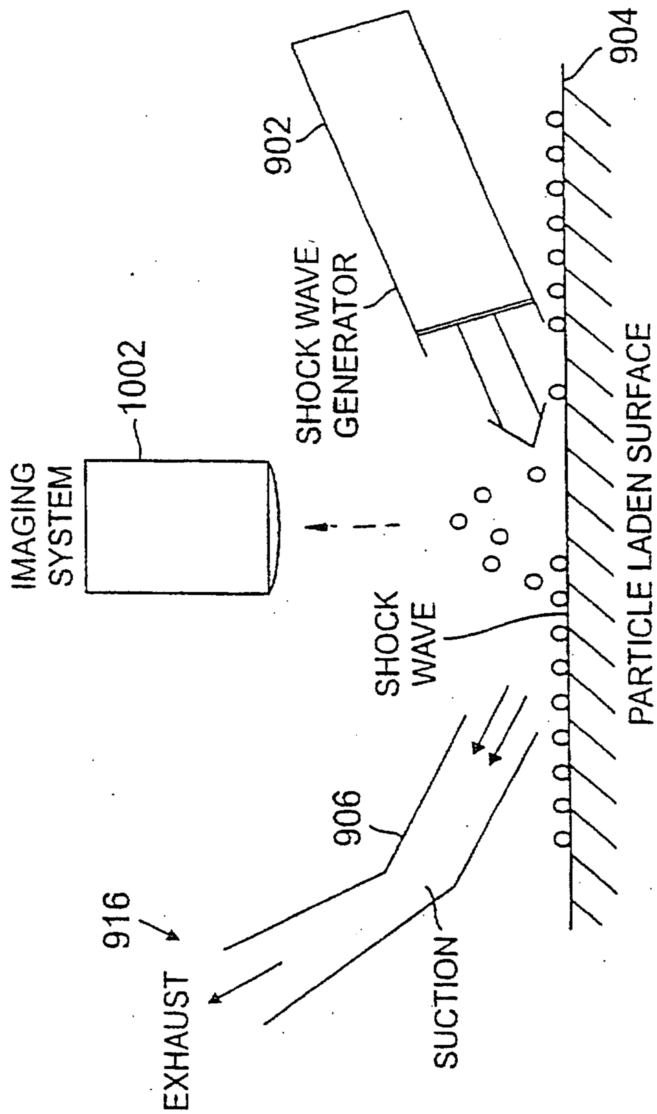

902
904
SHOCK WAVE GENERATOR
PARTICLE LADEN SURFACE
SHOCK WAVE
VALVE
906
930
924
916
EXHAUST
SUCTION
922
926
936
ANALYTICAL CARIER GAS
TRAP/SORBENT/ HEATER ASSEMBLY
VALVE
ANALYZER
916
EXHAUST

FIG. 9b



902
904
SHOCK WAVE GENERATOR
1002
IMAGING SYSTEM
SHOCK WAVE
PARTICLE LADEN SURFACE
906
916
EXHAUST
SUCTION

FIG. 10

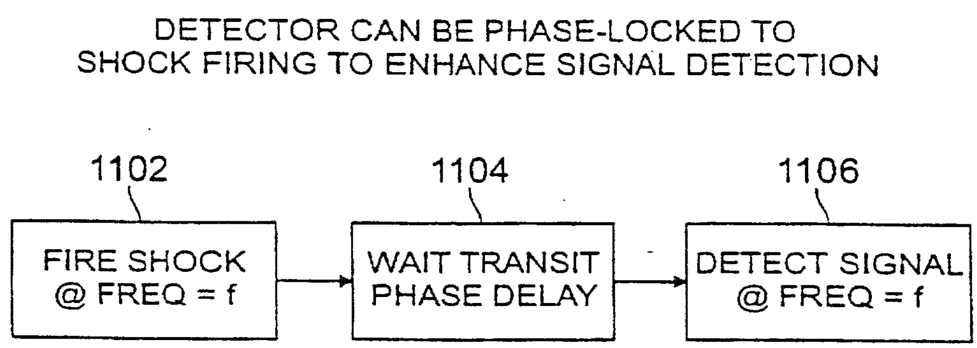

DETECTOR CAN BE PHASE-LOCKED TO
SHOCK FIRING TO ENHANCE SIGNAL DETECTION
1102
FIRE SHOCK
@ FREQ = f
1104
WAIT TRANSIT
PHASE DELAY
1106
DETECT SIGNAL
@ FREQ = f

FIG. 11

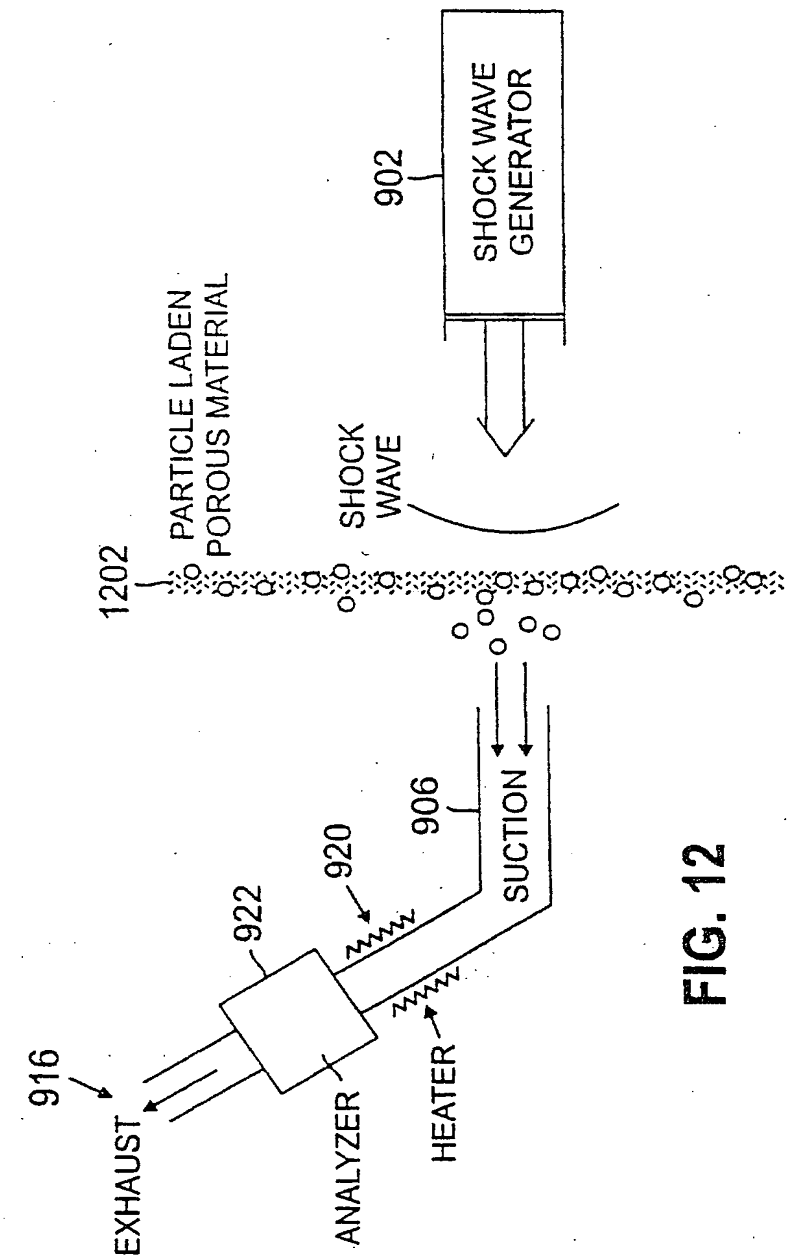

902
SHOCK WAVE GENERATOR
PARTICLE LADEN POROUS MATERIAL
SHOCK WAVE
1202
906
SUCTION
920
922
916
EXHAUST
ANALYZER
HEATER

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/16415

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G01N 25/54, 33/22; B08B 5/04, 7/04
US CL :Please See Extra Sheet.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 73/864; 134/17, 21, 37; 250/286, 287, 288; 422/88, 89; 436/96, 106, 107, 110, 155, 156, 173, 174, 181, 183

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,580,440 A (REID et al) 08 April 1986, see entire document, especially figure 7 and column 5.	1-50
Y	US 4,909,090 A (MCGOWN et al) 20 March 1990, see entire document.	1-50
Y	MONTZ, K. W. et al "Adhesion and Removal of Particulate Contaminants in a High-Decibel Acoustic Field" Powder Technology June 1988, Vol. 55, No. 2, pages 133 - 140, see entire document.	1-50
Y	US 4,987,286 A (ALLEN) 22 January 1991, see entire document.	1-50

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
04 JANUARY 1997	03 FEB 1997

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	ARLEN SODERQUIST
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0651

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/16415

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	LEE, S. J. et al "Shock Wave Analysis of Laser Assisted Particle Removal" Journal of Applied Physics 15 December 1993, Vol. 774, No. 12, pages 7044 - 7047.	1-50
Y	LEE, S. J. et al "Laser-Assisted Particle Removal from Silicon Surfaces" Microelectronic Engineering 1993, Vol. 20, pages 145 - 157, see entire document.	1-50
Y	OTANI, Y. et al "Removal of Fine Particles from Wafer Surface by Pulsed Air Jets" Kona 1994, No. 12, pages 155 - 160, see entire document.	1-50
Y	OTANI, Y. et al "Removal of Fine Particles from Smooth Flat Surfaces by Consecutive Pulse Air Jets" Aerosol Science and Technology 1995, Vol. 23, No. 4, 665 - 673, see entire document.	1-50
A	US 4,202,200 A (ELLSON) 13 May 1980.	1-50
A	FLAGAN R. C. "Compressible Flow Inertial Impactors" Journal of Colloid Interface Science June 1982, Vol. 87, No. 2, pages 291 - 299.	1-50
A	US 4,987,767 A (CORRIGAN et al) 29 January 1991.	1-50
A	SOLTANI M. et al "On Particle Adhesion and Removal Mechanisms in Turbulent Flows" Journal of Adhesion Science Technology 1994, Vol. 8, No. 7, pages 763 - 785.	1-50

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/16415

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

73/864; 134/17, 21, 37; 250/286, 287, 288; 422/88, 89; 436/96, 106, 107, 110, 155, 156, 173, 174, 181, 183

B. FIELDS SEARCHED
Electronic data bases consulted (Name of data base and where practicable terms used):

APS, STN search terms: sweep, shock?, inert?, acousti?, dust, partic?, remov?, turbul?, clean?, surface#, expols?, contraband, drug#, narcotic#, det##, detect?, determin?, measur?, monitor?, testing, probe#, probing, luggage, adhes?, jet#, wave#, enhanc?, laser#, pulsed, puff?, baggage, nozzle#

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